PATENT
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CONTROL OF FLUID FLOW IN THE PROCESSING OF AN OBJECT WITH A FLUID

FIELD OF THE INVENTION

The present invention in general relates to the field of semiconductor wafer processing. More particularly, the present invention relates to methods and apparatus for control of fluid flow in the processing of semiconductor wafers and other objects.

BACKGROUND OF THE INVENTION

The capacity and pressure requirements of a system can be shown with the use of a graph called a system curve. Similarly, a capacity versus pressure variation graph can be used to show a given pump's performance. As used herein, "capacity" means the flow rate with which fluid is moved or pushed by a pump, which is measured in units of volume per unit time, e.g., gallons per minute. The term "pressure" relative to fluids generally means the force per unit area that a fluid exerts on its surroundings. Pressure can depend on flow and other factors such as compressibility of the fluid and external forces. When the fluid is not in motion, that is, not being pumped or otherwise pushed or moved, the pressure is referred to as static pressure. If the fluid is in motion, the pressure that it exerts on its surroundings is referred to as dynamic pressure, which depends on the motion.

The variety of conditions, ranges, and fluids for which it can be desirable to measure pressure has given rise to numerous types of pressure sensors or transducers, such as but not limited to gage sensors, vacuum sensors, differential pressure sensors, absolute pressure sensors, barometric sensors, piezoelectric pressure sensors, variable-impedance transducers, and resistive pressure sensors. One problem with the use of pressure transducers is that, depending on the composition and materials used in the transducer and the composition of the fluid being measured, the transducer can break down and contaminate the system. Another problem with the use of pressure transducers is that their accuracy can vary both with temperature changes and over time. Temperature changes and large pressure changes typically occur during semiconductor wafer processing with supercritical fluids. During wafer processing, the unreliable accuracy of pressure sensors can adversely impact quality control and affect yield. It would be advantageous to have a fluid flow control system that does not include pressure transducers. It would be desirable to eliminate the need for using pressure transducers in controlling the flow of a fluid during semiconductor wafer processing.

Flow meters are commonly used to measure a fluid flow in the processing of semiconductor wafers and other objects. Problems commonly associated with flow meters include clogging, contamination, leaks, and maintenance costs. It would be advantageous to have a fluid flow control system that does not include flow meters. It would be desirable to reduce contamination in semiconductor wafer processing by elimination of the contamination typically associated with the use of flow meters.

The use of pumps in the processing of semiconductor wafers and other objects is known. Pumps induce fluid flow. The term "head" is commonly used to measure the kinetic energy produced by a pump. By convention, head refers to the static pressure produced by the weight of a vertical column of fluid above the point at which the pressure is being described—this column's height is called the static head and is expressed in terms of length, e.g., feet, of liquid.

"Head" is not equivalent to the "pressure." Pressure has units of force per unit area, e.g., pound per square inch, whereas head has units of length or feet. Head is used instead of pressure to measure the energy of a pump because, while the pressure of a pump will change if the specific gravity (weight) of the fluid changes, the head will not change. Since it can be desirable to pump different fluids, with different specific gravities, it is simpler to discuss the head developed by the pump, as opposed to pressure, neglecting the issue of the specific gravity of the fluid. It would be desirable to have a fluid flow control system that includes a pump.

There are numerous considerations and design criteria for pump systems. Pump performance curves have been used as tools in the design and analysis of pump systems. FIG. 1 is a representative illustration of a pump performance curve for a centrifugal pump with various impeller diameters, for the purpose of showing the relationship between the capacity (flow rate) and total dynamic head of an exemplary pump in the prior art. As a general rule with centrifugal pumps, an increase in flow causes a decrease in head. Typically, a pump performance curve also shows the rotational speed in revolutions per minute, net positive suction head (NPSH) required, which is the amount of NPSH the pump requires to avoid cavitation, power requirements, and other information such as pump type, pump size, and impeller size. For example, the pump size, 1-1/2 x 3 - 6, shown in the upper part of the centrifugal pump curve illustrated in FIG. 1, indicates a 1-1/2 inch discharge port, a 3 inch suction port, and a maximum nominal impeller size of 6 inches. As depicted in FIG. 1, the several curves that slope generally downward from left to right across the graph show the actual performance of the pump at various impeller diameters. Pump system performance can vary for every application based on the slope of the

pump performance curve and its relationship with any specific system curve.

What is needed is an apparatus for and method of controlling a fluid flow for use in the processing of an object with a fluid, such that contaminants in the fluid are minimized. What is needed is an apparatus for and method of controlling a fluid flow that does not include flow meters for controlling the fluid flow. What is needed is an apparatus for and method of controlling a fluid flow that does not include pressure transducers for controlling the fluid flow.

SUMMARY OF THE INVENTION

In a first embodiment of the present invention, an apparatus for control of a fluid flow includes a measuring means for measuring a pump performance parameter and a controller means for adjusting a fluid flow in response to in the pump performance parameter.

In a second embodiment of the invention, an apparatus for control of a fluid flow includes a measuring means for measuring a pump performance parameter and a means for comparing a measured pump performance parameter to a predetermined target pump performance parameter. The apparatus also includes a controller means for adjusting a fluid flow in response to a difference in the measured pump performance parameter and the predetermined target pump performance parameter.

In a third embodiment of the invention, an apparatus for control of a fluid flow includes a pump and a sensor for measuring a pump performance parameter. The apparatus also includes a controller for adjusting operation of the pump to control a fluid flow in response to the pump performance parameter.

In a fourth embodiment, a system for supercritical processing of an object includes a means for performing a supercritical process. The system also includes a means for measuring a pump performance parameter and a means for adjusting operation of a pump to control a fluid flow in response to the pump performance parameter.

In a fifth embodiment, a method of control of a fluid flow comprises the steps of measuring a pump performance parameter and adjusting a fluid flow in response to the pump performance parameter.

In a sixth embodiment, a method of eliminating flow meter contamination in semiconductor wafer processing with a fluid comprises the steps of measuring a pump operational parameter and adjusting operation of a pump to control a fluid flow in response to the pump operational parameter.

In a seventh embodiment, a method of control of a fluid flow includes the step of measuring a pump performance parameter. The method also includes the steps of comparing a measured pump performance parameter to a predetermined target pump performance parameter and adjusting a fluid flow in response to a difference in the measured pump performance parameter and the predetermined target pump performance parameter.

In an eighth embodiment, a method of control of a fluid flow in a supercritical processing system includes the steps of defining a system curve including a point of operation and using the system curve to define at least one of a predetermined pump speed, voltage, electric current, and electric power. The method includes the step of measuring performance of a pump to obtain at least one of a measured pump speed, voltage, electric current, and electric power. The method also includes the steps of comparing at least one of a measured pump speed, voltage, electric current, and electric power to at least one of a predetermined pump speed, voltage, electric current, and electric power and adjusting operation of a pump to control a fluid flow in response to a difference in at least one of a measured pump speed, voltage, electric current, and electric power and at least one of a predetermined pump speed, voltage, electric current, and electric power.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be better understood by reference to the accompanying drawings of which:

FIG. 1 is an representative illustration of a pump performance curve for an centrifugal pump with various impeller diameters, for the purpose of showing the relationship between the capacity and total dynamic head of an exemplary pump in the prior art.

FIG. 2 is a representative illustration of a capacity versus pressure variation graph, showing a system curve, in accordance with embodiments of the present invention.

FIG. 3 is a schematic illustration of an apparatus for control of a fluid flow, in accordance with embodiments of the present invention.

FIG. 4 is a schematic illustration of an apparatus for control of a fluid flow, in accordance with embodiments of the present invention.

FIG. 5 is a flow chart showing a method of control of a fluid flow, in accordance with embodiments of the present invention.

FIG. 6 is a flow chart showing a method of eliminating contamination in semiconductor

wafer processing with a fluid, in accordance with embodiments of the present invention.

FIG. 7 is a flow chart showing a method of showing a method of control of a fluid flow, in accordance with embodiments of the present invention.

FIG. 8 is a flow chart showing a method of control of a fluid flow in a supercritical processing system, in accordance with embodiments of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is directed to an apparatus for and methods of control of a fluid flow. For the purposes of the invention and this disclosure, "fluid" means a gaseous, liquid, supercritical and/or near-supercritical fluid. In certain embodiments of the invention, "fluid" means gaseous, liquid, supercritical and/or near-supercritical carbon dioxide. It should be appreciated that solvents, co-solvents, chemistries, and/or surfactants can be contained in the carbon dioxide. For purposes of the invention, "carbon dioxide" should be understood to refer to carbon dioxide (CO_2) employed as a fluid in a liquid, gaseous or supercritical (including near-supercritical) state. "Supercritical carbon dioxide" refers herein to CO_2 at conditions above the critical temperature (30.5° C) and critical pressure (7.38 MPa). When CO_2 is subjected to pressures and temperatures above 7.38 MPa and 30.5° C, respectively, it is determined to be in the supercritical state. "Near-supercritical carbon dioxide" refers to CO_2 within about 85% of critical temperature and critical pressure. For the purposes of the invention,"object" typically refers to a semiconductor wafer for forming integrated circuits, a substrate and other media requiring low contamination levels. As used herein, "substrate" includes a wide variety of structures such as semiconductor device structures typically with a deposited photoresist or residue. A substrate can be a single layer of material, such as a silicon wafer, or can include any number of layers. A substrate can comprise various materials, including metals, ceramics, glass, or compositions thereof.

Referring now to the drawings, and more particularly to FIG. 2, there is shown a representative illustration of a capacity versus pressure variation graph, including the curves that correspond to pump performance at various impeller diameters. FIG. 2 also shows a system curve, in accordance with embodiments of the present invention. In accordance with the invention, a system curve, such as depicted in FIG. 2, shows the change in flow with respect to head of the system. The system curve can be based on various factors such as physical layout of the system, process conditions, and fluid characteristics. The point "PO" on the system curve

shown in FIG. 2 defines the point of operation of the system, based on a constant pump speed (rpm) and fixed fluid conditions. For purposes of the invention, "fixed fluid conditions" means fixed temperature and fixed pressure. The point "P" on the pump power curve shown in FIG. 2 defines the power required with respect to the point of operation. The point "V" defines the volumetric flow rate with respect to the point of operation.

FIG. 3 is a schematic illustration of an apparatus 300 for control of a fluid flow, in accordance with embodiments of the present invention. As shown in FIG. 3, in the preferred embodiment of the invention, an apparatus 300 for control of a fluid flow comprises a measuring means 325 for measuring a pump performance parameter and a controller means 350 for adjusting a fluid flow in response to a change in the pump performance parameter. In certain embodiments, the measuring means 325 comprises at least one sensor for measuring pump speed, voltage, electric current, and/or electric power. In certain embodiments, the measuring means comprises a voltage sensor, an electric current sensor, an electric power sensor, and/or a multi-component sensor. Preferably, the controller means 350 comprises a process control computer 340 for adjusting operation of at least one of a flow-control means 317 and a pump 315. In certain embodiments, the flow-control means comprises at least one of a valve, a pneumatic actuator, an electric actuator, a hydraulic actuator, and a micro-electric actuator. In one embodiment, the pump comprises a centrifugal pump. Preferably, the fluid comprises at least one of gaseous, liquid, supercritical and near-supercritical carbon dioxide. It should be understood that solvents, co-solvents and surfactants can be contained in the carbon dioxide.

According to one embodiment of the invention, an apparatus for control of a fluid flow comprises a measuring means for measuring a pump performance parameter; a means for comparing a measured pump performance parameter to a predetermined target pump performance parameter; and a controller means for adjusting a fluid flow in response to a difference in the measured pump performance parameter and the predetermined target pump performance parameter. In one embodiment, the controller means comprises a process control computer for adjusting operation of at least one of a flow-control means and a pump in response to a difference in the measured pump performance parameter and the predetermined target pump performance parameter. It should be appreciated that any means for determining a difference in the measured pump performance parameter and the predetermined target pump performance parameter should be suitable for implementing the present invention, such as a process control computer. In one embodiment, the flow-control means comprises means for adjusting a system

element to change the resistance to flow. In certain embodiments of the invention, an apparatus for control of a fluid flow includes means for delivering the fluid flow to means for performing a supercritical process. In certain embodiments, the means for performing a supercritical process comprises a processing chamber and means for circulating at least one of a gaseous, liquid, supercritical and near-supercritical fluid within the processing chamber.

FIG. 4 is a schematic illustration of an apparatus 400 for control of a fluid flow, in accordance with embodiments of the present invention. As shown in FIG. 3, in one embodiment of the invention, the apparatus 400 includes a pump 415 for moving a fluid and a sensor 425 for measuring a pump performance parameter. In one embodiment, the pump 415 comprises a centrifugal pump. It should be appreciated that while the invention contemplates the use of a centrifugal pump, various different pumps can be used without departing from the spirit and scope of the invention. Preferably, the fluid comprises at least one of gaseous, liquid, supercritical and near-supercritical carbon dioxide. It should be understood that solvents, co-solvents and surfactants can be contained in the carbon dioxide.

In one embodiment of the invention, the apparatus 400 includes a controller 435 for adjusting operation of the pump to control a fluid flow in response to the pump performance parameter. In one embodiment, the controller 435 includes a process control computer 440. In certain embodiments, the pump performance parameter comprises at least one of a pump speed, voltage, electric current, and electric power.

In one embodiment, a system for supercritical processing of an object comprises: a means for performing a supercritical process; a means for measuring a pump performance parameter; and a means for adjusting operation of a pump to control a fluid flow in response to the pump performance parameter. In certain embodiments, the means for performing a supercritical process includes a processing chamber. The details concerning one example of a processing chamber are disclosed in co-owned and co-pending United States Patent Applications, Serial No. 09/912,844, entitled "HIGH PRESSURE PROCESSING CHAMBER FOR SEMICONDUCTOR SUBSTRATE," filed July 24, 2001, Serial No. 09/970,309, entitled "HIGH PRESSURE PROCESSING CHAMBER FOR MULTIPLE SEMICONDUCTOR SUBSTRATES," filed October 3, 2001, Serial No. 10/121,791, entitled "HIGH PRESSURE PROCESSING CHAMBER FOR SEMICONDUCTOR SUBSTRATE INCLUDING FLOW ENHANCING FEATURES," filed April 10, 2002, and Serial No. 10/364,284, entitled "HIGH-PRESSURE PROCESSING CHAMBER FOR A SEMICONDUCTOR WAFER," filed February 10, 2003,

the contents of which are incorporated herein by reference.

In certain embodiments of the invention, the means for performing a supercritical process includes a means for circulating at least one of a gaseous, liquid, supercritical and near-supercritical fluid within the processing chamber. Preferably, the fluid comprises carbon dioxide. It should be appreciated that any combination of solvents, co-solvents and surfactants can be contained in the carbon dioxide. In certain embodiments of the invention, the pump performance parameter comprises a pump speed, voltage, current, and power.

FIG. 5 is a flow chart showing a method of control of a fluid flow, in accordance with embodiments of the present invention. In step 510, a pump performance parameter is measured. In one embodiment of the invention, the pump performance parameter comprises at least one of a pump speed, voltage, electric current, and electric power. In step 520, a fluid flow is adjusted in response to the performance parameter. Preferably, the fluid comprises at least one of gaseous, liquid, supercritical and near-supercritical carbon dioxide. It should be appreciated that solvents, co-solvents, chemistries, and/or surfactants can be contained in the carbon dioxide.

FIG. 6 is a flow chart showing a method of eliminating contamination in semiconductor wafer processing with a fluid, in accordance with embodiments of the present invention. In step 610, a pump operational parameter is measured. In step 620, operation of a pump is adjusted to control a fluid flow in response to the performance parameter. Preferably, the fluid comprises at least one of gaseous, liquid, supercritical and near-supercritical carbon dioxide. It should be appreciated that solvents, co-solvents, chemistries, and/or surfactants can be contained in the carbon dioxide.

FIG. 7 is a flow chart showing a method of control of a fluid flow, in accordance with embodiments of the present invention. In step 710, a pump performance parameter is measured. In step 720 a measured pump performance parameter is compared to a predetermined target pump performance parameter. In step 730, a fluid flow is adjusted in response to a difference in the measured pump performance parameter and the predetermined target pump performance parameter.

FIG. 8 is a flow chart showing a method of control of a fluid flow in a supercritical processing system, in accordance with embodiments of the present invention. In step 810, a system curve is defined including a point of operation. In step 820, the system curve is used to define at least one of a predetermined pump speed, voltage, electric current, and electric power. In step 830, performance of a pump is measured to obtain at least one of a measured pump speed,

voltage, electric current, and electric power. In step 840, at least one of a measured pump speed, voltage, electric current, and electric power is compared to at least one of a predetermined pump speed, voltage, electric current, and electric power. In step 850, operation of a pump is adjusted to control a fluid flow in response to a difference in at least one of a measured pump speed, voltage, electric current, and electric power and at least one of a predetermined pump speed, voltage, electric current, and electric power.

While the processes and apparatus of this invention have been described in detail for the purpose of illustration, the inventive processes and apparatus are not to be construed as limited thereby. It will be readily apparent to those of reasonable skill in the art that various modifications to the foregoing preferred embodiments can be made without departing from the spirit and scope of the invention as defined by the appended claims.